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Characterization of the Resulting Incapacitation Following Unexpected +Gz-Induced Loss of Consciousness

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+G_z-induced loss of consciousness (G-LOC) results in incapacitation which can be characterized by the unconscious period (absolute incapacitation) and a subsequent period of confusion/disorientation (relative incapacitation). The sum of the absolute and relative incapacitation periods represents the total incapacitation period and may be equated to the overall length of time a pilot would be in uncontrolled flight should G-LOC occur. Reviewing the centrifuge induced G-LOC episodes in 55 subjects allowed a detailed description of G-LOC. The absolute incapacitation period was 16.6 s with the subsequent relative incapacitation being 14.5 s resulting in an overall total incapacitation of 31 s. The G-LOC incapacitation was dependent on the rate of onset of the +G_z-stress and the +G_z level where G-LOC occurred. G-LOC episodes could be subdivided into 2 separate types: Type I being shorter unconsciousness episodes without convulsive movements, and Type II being longer unconsciousness with more frequently associated dream states and convulsive type movements. This detailed description of G-LOC allows a more complete understanding of the phenomenon and establishes the basis for research toward decreasing the resulting incapacitation from G-LOC. Minimizing G-LOC incapacitation and enhancing recovery should enhance safety in the aviation environment of the high-performance-fighter aircraft pilot.

ALTHOUGH MUCH PROGRESS has been made in providing optimum protection for aircrewmen flying high performance fighter-type aircraft, episodes of +G_z-induced loss of consciousness (LOC) continue to occur. The very high onset +G_z (VHOG) capabilities of existing aircraft which can sustain the +G_z force will predispose aircrew to LOC episodes as long as there is a difference in the levels of the heart and brain within the +G_z field. Detailed knowledge of the characteristics of +G_z-induced LOC are essential for estimating the potential problems that can result from inflight LOC and for adding further insight into potential methods of prevention, intervention, and enhanced recovery. Advanced development of methods to reduce the time of incapacitation are dependent on knowing the length and characteristics of the typical LOC episode. Previous studies documented the average time of absolute incapacitation (unconsciousness) to be 15 s (5). It was evident from those studies that a relative incapacitation period (confusion/disorientation) immediately followed the absolute incapacitation period (unconsciousness). Further investigation of both absolute- and relative-incapacitation periods resulting from deliberate +G_z-induced LOC confirmed that absolute incapacitation was on the order of 15 s with the relative incapacitation extending the overall incapacitation to approximately 30 s (depending on the +G_z-onset rate) (2).

The current study reports the characteristics of accidental unexpected +G_z-induced LOC episodes resulting from +G_z exposures on the USAF School of Aerospace Medicine (USAFSAM) human centrifuge. These results provide the basis for advanced techniques to evaluate optimum methods of intervention to minimize +G_z-induced LOC incapacitation.

MATERIALS AND METHODS

Subjects exposed to +G_z stress on the USAFSAM centrifuge are not routinely taken to LOC; however,

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The research reported was performed by members of the Crew Technology Division of the USAF School of Aerospace Medicine, Brooks AFB, Texas. The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 169-3.

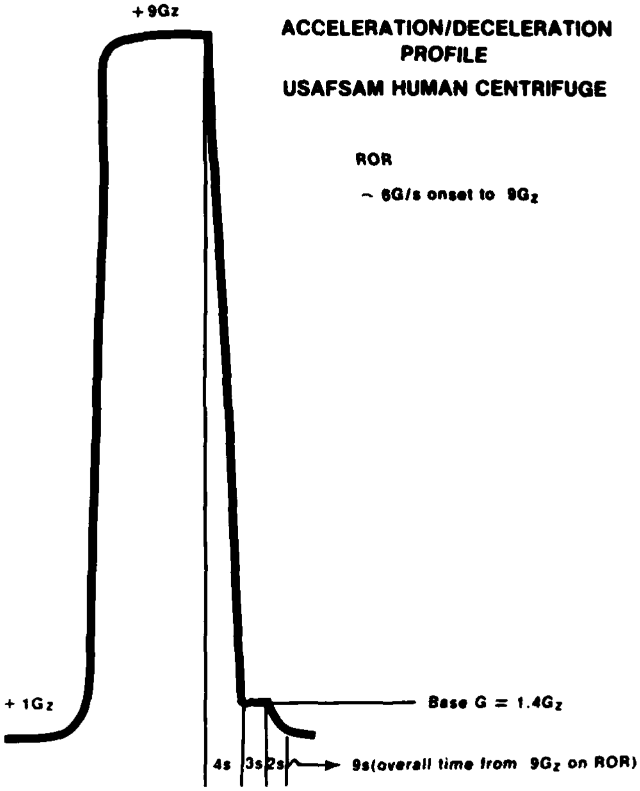

Fig. 1. Rapid onset rate +Gz acceleration profile with the offset rate-time description.

LOC episodes do occur accidentally during exposure to very high onset sustained $+G_z$. Current experimentation and training requires frequent exposure to $+9\ G_z$ for 15 s or more using $+6\ G \cdot s^{-1}$ onset rates. Inadvertent LOC is almost impossible to prevent using current protective methods and monitoring techniques. All exposures to $+G_z$ stress are routinely videotaped, with the LOC episodes being archived in the centrifuge medical videotape library as part of the subject's medical record. All subjects exposed to acceleration stress were considered healthy, asymptomatic, and had successfully passed a USAF flying class II physical examination (at a minimum). The subjects consisted of experimental volunteer subjects, students undergoing $+G_z$ orientation training while attending courses at USAFSAM, and aircrew.

The onset rate of the $+G_z$ exposures was of two types: 1) rapid onset runs (ROR), $2.5\ G \cdot s^{-1}$ and $6.0\ G \cdot s^{-1}$, and 2) gradual onset runs (GOR), $0.1\ G \cdot s^{-1}$. The offset (deceleration) rate of the $+G_z$ exposure depended on the onset rate. For the ROR, the offset rate was more rapid, taking approximately 9 s for a maximum $+9\ G_z$ exposure to return to $+1.0\ G_z$ (see Fig. 1). For the GOR, the offset rate was longer, taking approximately 15 s for a maximum $+9\ G_z$ exposure to return to $+1.0\ G_z$ (see Fig. 2). The net result of the offset (deceleration) rate is such that for GOR exposures the exposure to $+G_z$ is longer than on ROR exposures.

The USAFSAM centrifuge is equipped with an auditory warning horn. This is a loud, noxious tone which can be initiated by the medical monitor upon recognition of the loss of consciousness episode and which can be eliminated manually by the subject upon recovery following LOC. The horn produces a continuous sound pressure level of 85–90 dbA at the average subject's ear level in the centrifuge (sound-level meter, 15–65 A). In addition, there is a "master caution" light in front of the subject which may be illuminated by the medical monitor upon recognition of the LOC episode and extinguished by the subject upon recovery. The master caution light is the same as that used in current USAF aircraft. The time required to extinguish these auditory and visual warning systems provides a relatively simple measure of the incapacitation period following accidental LOC. All subjects are briefed on these LOC monitoring systems

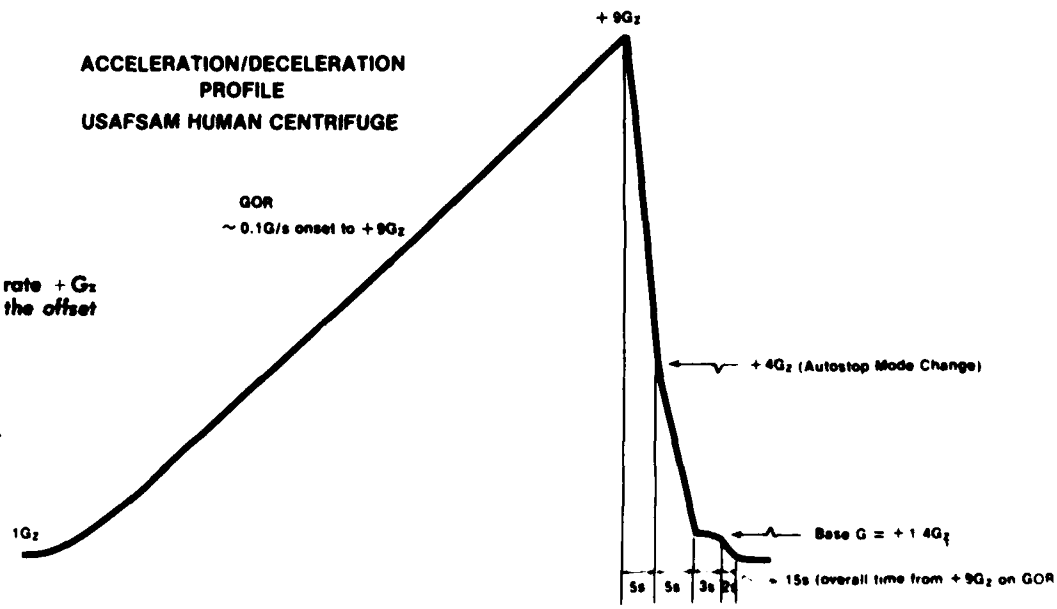

Fig. 2. Gradual onset rate +Gz acceleration profile with the offset rate-time description.

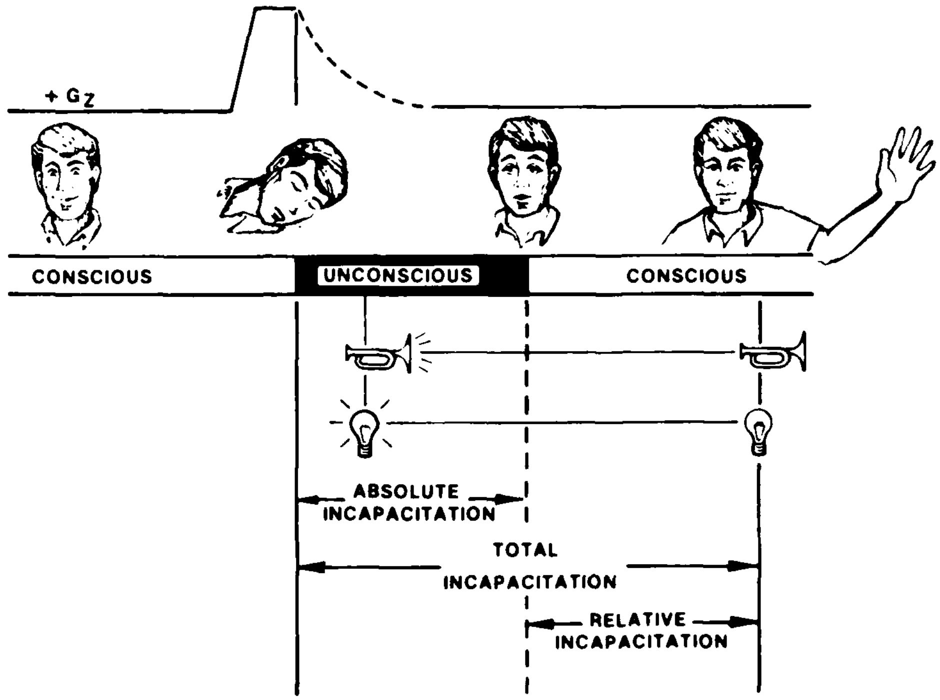

Fig. 3. Schematic of the incapacitation resulting from $+G_z$-induced loss of consciousness. A visual master caution light and auditory tone were used to determine the end of the relative incapacitation period.

prior to exposure to $+G_z$ stress. The auditory horn was installed first on the centrifuge, and was later followed by installation of the master caution light which was considered currently aircraft operational and, therefore, more cockpit applicable. Of the 55 subjects, 52 were exposed to and responded to the horn, and 27 of the 55 subjects were exposed to and responded to the master caution light. Each subject was instructed to react immediately when either the light or horn was activated. When both systems were activated, the order of response was left to the subject's discretion.

The total incapacitation was defined as the period of time from initial recognition of the onset of LOC (head drop/relaxation) until the subject eliminated the auditory tone (auditory end point) and extinguished the master caution light (visual end point). The absolute incapacitation was defined as the period from initial recognition of the LOC until the subject subjectively appeared to the investigator to be responsive. The relative incapacitation period was the difference between the total incapacitation period and the absolute incapacitation period. A flow diagram of the experimental conditions for determining these incapacitation periods is shown in Fig. 3. Multiple observers reviewed the videotaped LOC episodes. Subjective estimation of the onset of the LOC episode and the return of consciousness (absolute incapacitation) by multiple observers were extremely close, varying no more than ±1 s on all LOC episodes in the study. The mean of the measurements from the observers was the time reported.

All associated symptoms and subjective feelings were documented from reviewing the LOC videotape record. Means (± S.D.) were calculated for all incapacitation periods. Means for various subgroups of the total LOC data base were also calculated. The initial LOC episode experienced by 55 different subjects constituted the LOC data base.

RESULTS

There were 55 male subjects who suffered an initial loss of consciousness episode included in the analysis. The mean age for the group was 32.7 (± 6.2 S.D.) years, ranging from 24 to 48 years. The mean $+G_z$ level of the centrifuge exposure which resulted in the LOC was $+7.9$ (1.2) G_z (maximum $+9$ G_z; minimum $+4$ G_z). The percentage of subjects having an LOC

TABLE I. INCAPACITATION TIMES (± S.D.) FOR UNEXPECTED $+G_z$-INDUCED LOSS OF CONSCIOUSNESS EPISODES IN THE 55 SUBJECTS

Incapacitation Period	Number of Subjects	Mean (± S.D.) time (s)	Maximum time (s)	Minimum time (s)
Absolute	55	16.6 (5.9)	30	5
Total (auditory)	52	31.0 (11.7)	63	10
Total (visual)	27	31.4 (12.2)	64	15
Relative (auditory)	52	14.5 (9.6)	51	1
Relative (visual)	27	14.9 (11.0)	50	4

episode for the G-onset rate of 0.1 G·s^{-1} was 62%, 2.5 G·s^{-1}, 2%, and 6.0 G·s^{-1}, 36%.

The incapacitation times for the LOC episodes are shown in Table I. The mean absolute incapacitation time for all LOC episodes was 16.6 (5.9)s with a mean total incapacitation measured by the auditory tone of 31.0 (11.7s) and a mean total incapacitation measured by the visual "master caution" light of 31.4 (12.2)s. The mean difference between the responses to the auditory tone compared to the visual light was 1.5 s, indicating that subjects responded more rapidly to the auditory tone. The mean relative incapacitation measured by the auditory tone was 14.5 (9.6)s and 14.9 (11)s measured by the visual light.

The time of absolute incapacitation was correlated with the $+G_z$ level at which the LOC occurred ($r = +0.38$). The lower the $+G_z$ at which the LOC occurred, the shorter the time of absolute incapacitation. The total incapacitation (auditory) revealed a similar correlation. The relative incapacitation (measured using either the auditory or visual end points) was not related to the $+G_z$ level at which the LOC occurred.

The effect of onset rate on the incapacitation was evaluated by separating the data into GOR (0.1 G·s^{-1}) and ROR (2.5 and 6.0 G·s^{-1}) subgroups. The mean absolute incapacitation for the GOR subgroup ($N = 34$) was 19.3 (5.4)s as compared to the ROR subgroup ($N = 21$) which was 12.2 (3.8)s. This difference in absolute incapacitation was significant at the $p < 0.0001$ level. The total incapacitation as measured by the auditory end point also revealed a significant difference ($p < 0.002$) between the GOR subgroup 34.9 (10.4)s, as compared to the ROR subgroup, 24.8 (11.1)s. The relative incapacitation was not significantly different relative to either type of $+G_z$ exposure.

Of the subjects, 17 (31%) experienced convulsive-like flail movements of the head and extremities during the LOC episodes (see Table II). The mean absolute incapacitation period for the subgroup with flail movements was 20.4 (5.2)s, as compared to the non-flail subgroup whose absolute incapacitation was 14.9 (5.4)s, significant at the $p < 0.001$ level. The total incapacitation to an auditory end point for the flail subgroup was 37.3 (10.1)s, as compared to 28.2 (11.3)s for the non-flail subgroup which was significantly different $p < 0.01$. The total incapacitation to a visual end point and the relative incapacitation periods (both auditory and visual end points) were also prolonged for the flail subgroup, although they did not reach a statistically significant difference level.

Early in the experimentation there was a tendency for the non-medical centrifuge operation crew to verbally interact with the subject who experienced the LOC episode. A total of 10 subjects were considered to have central observer interaction (COI). Statistical analysis failed to reveal any differences between any of the incapacitation variables for the COI subgroup. For this reason, no further differential of the non-COI and COI groups was made. Conceivably the verbal stimulus associated with COI could have reduced the relative incapacitation, and subsequently the total incapacitation; however, the limited interaction evidently exerted a minimal effect on LOC recovery. No effect on recovery times was found in other studies that involved COI (2).

DISCUSSION

The mean absolute incapacitation resulting for all unexpected $+G_z$-induced loss of consciousness episodes was 16.6 s. This agrees closely with previous work which revealed a mean absolute incapacitation of 15 s (5). The maximum absolute incapacitation was 30 s. Although only 16 (29%) of the LOC subjects had electrocardiographic monitoring during the $+G_z$ exposure, none of the subjects were observed to have rate or rhythm disturbances which could have exacerbated the period of incapacitation. Certain electrocardiographic irregularities such as cardiac asystole have been noted to extend the time of incapacitation (6). The true incidence of electrocardiographic changes in this group of centrifuge-exposed subjects remains unknown.

Knowledge of the predicted time of incapacitation has proven to be extremely useful in defining the expected incapacitation resulting from unobserved $+G_z$-induced LOC in flight. Since fatal aircraft mishaps require reconstruction of the probable sequence of events, this information is of prime importance to assist accident/mishap investigations. Actual inflight $+G_z$-induced LOC incidents or accidents have confirmed that the time of absolute incapacitation is on the order of 15 s. Our current work has further defined the absolute incapacitation to be dependent on the $+G_z$-onset rate (and perhaps the offset rate) and confirms the work of others (2). The offset rate (based on the time to return to +1.0 G_z) of the $+G_z$ for our ROR exposures was

TABLE II. $+G_z$-LOSS OF CONSCIOUSNESS INCAPACITATION TIMES FOR THE FLAIL/NON-FLAIL SUBGROUPS (A = AUDITORY STIMULATION; V = VISUAL STIMULATION).

Subgroup	G-LOC	Absolute Incap	Total Incap(A)	Total Incap(V)	Relative Incap(A)	Relative Incap(V)
Flail	8.1(1.1) (N = 17)	20.4(5.2)* (N = 17)	37.3(10.1)** (N = 16)	36.6(12.1) (N = 9)	17.3(11.7) (N = 16)	16.6(14.[illegible]) (N = 9)
Non-flail	7.3(1.3) (N = 38)	14.9(5.4)* (N = 38)	28.2(11.3)** (N = 36)	28.8(11.7) (N = 18)	13.3(8.3) (N = 36)	14.0(9.[illegible]) (N = 18)

*p < 0.0001 **p < 0.01

0.9 $G \cdot s^{-1}$ and 0.5 $G \cdot s^{-1}$ for our GOR exposures. Offset rates during inflight G-LOC incidents have been observed to be 0.5 $G \cdot s^{-1}$. Since most inflight +G_z-LOC episodes would be expected to result from very rapid onset +G_z (as contrasted to the centrifuge GOR runs), the absolute incapacitation resulting from the ROR data would be more applicable to fighter aircraft operations. We are, therefore, able to more accurately define the probable absolute incapacitation inflight during aerial combat flying to be approximately 12 s. This absolute incapacitation period of 12 s has been confirmed in an actual F-16 G-LOC incident (1). This absolute incapacitation is extremely important in defining methods for interacting with unconscious aircrewmen and decreasing the time of incapacitation. It is of vital importance to accurately know the length of incapacitation for development of aircraft physiologic autorecovery systems.

In previous research we recognized that there was a period of relative incapacitation following the absolute incapacitation period. The sum of the absolute and relative incapacitation periods results in the total incapacitation resulting from +G_z-induced LOC. The total incapacitation resulting from +G_z-induced LOC is a measure of the overall period of time that a pilot may expect not to be in full aircraft control or fully utilizing his weapon system. This total incapacitation which consists of the absolute and relative incapacitation would be expected to be approximately 31 s (31.0 s as measured by an auditory response and 31.4 s as measured by a visual response). The absolute incapacitation is much less subject to individual variation as compared to the relative incapacitation; therefore, the variability of the total incapacitation is most frequently due to the relative incapacitation following the +G_z-induced LOC. The total incapacitation could be expected to be the length of time transpiring before an aircrew could fully regain full control of his weapon system since it measured the time from the onset of the LOC until purposeful movement was possible. These incapacitation times are based on immediate deceleration upon recognition of the LOC. Whether or not inflight LOC will result in immediate deceleration is likely but not assured.

The relative incapacitation is an area deserving much attention from aeromedical researchers since the subject (aircrew) may be more likely to have positive reorienting interaction during this period, thus reducing the time necessary for recovery. The relative incapacitation is roughly equivalent to the absolute incapacitation period, the mean relative incapacitation being 14.5 s (14.5 s as measured by the auditory tone and 14.9 s by the visual end point).

Considering all subjects, the auditory tone was more frequently responded to prior to the visual "master caution" light. The mean response difference for all subjects who were presented both stimuli was 1.5 (7.6)s, meaning that the response to extinguish the auditory tone was on the average 1.5 s quicker than the response to extinguish the master caution light. When experienced tactical aircrew were separated as a group (N = 37), as compared to experimental non-aircrew subjects (N = 15), the aircrew responded more quickly to the master caution light as compared to the auditory tone (Table III). In non-aircrew the differential response to the auditory and visual stimuli was equal, whereas for aircrew 58% (as compared to 26% for auditory) responded initially to a visual, familiar master caution light. It is evident that more sophisticated research is necessary to determine the optimum placement and stimulus for monitoring +G_z-induced LOC incapacitation and further to evaluate the optimum method to interact with a potentially incapacitated aircrewman. The data from this research reveal a trend for aircrew to respond to a familiar master caution light rather than an *unfamiliar* auditory stimulus. The optimum stimulus for achieving recovery in the minimum time possible is a highly desirable goal. Time is critical during an inflight emergency, time periods of 5 s or less may allow recovery of the aircraft and its crew. It is of vital importance to understand the time-critical nature of +G_z-induced loss of consciousness and the time needed for successful aircraft recovery.

We have previously reported the existence of convulsive type movements of the extremities which occur during the absolute incapacitation period (2). Inflight episodes of LOC have also had documented occurrences

TABLE III. DIFFERENTIAL TOTAL INCAPACITATION TO AUDITORY RESPONSE (A) AND VISUAL (V) STIMULI OF AIRCREW AND NON-AIRCREW. MEAN (± S.D.)

Subgroup	Total Incapacitation (A)s	Total Incapacitation (V)s
Total	31.0(11.7)	31.4(12.2)
	(N = 52)	(N = 27)
Aircrew	31.7(10.9)	29.3(10.3)
	(N = 37)	(N = 19)
Non-aircrew	29.3(13.6)	36.3(15.6)
	(N = 15)	(N = 8)
Aircrew initial response	58% to Master Caution 26% to Auditory Tone	
Non aircrew initial response	40% to Master Caution 40% to Auditory Tone	

TABLE IV. TIME OF INCAPACITATION ASSOCIATED WITH +G_z-INDUCED LOC SYMPTOMS. MEAN (±S.D.)

Subject #	Symptoms Dream	Flail	Absolute Incap (A)s	Total Incap (A)s	Relative Incap (A)
1	+	+	15	28	13
2	+	+	28	45	17
3	+		12	15	3
4	+	+	26	39	13
5	+		25	43	18
6	+	+	23	43	20
7	+	+	15	25	10
Total/Mean	7	5	20.6(6.3)	34.0(11.4)	13.4(5.7)

of the flail movements (3). The potential for initiation of critical aircraft systems is real and has been observed resulting from LOC induced flail movements. Besides movement of the flight controls, the possibility of high speed gear extension; canopy release, or other high risk manipulations could result from such flail-like movements in an unconscious or disoriented state. It is important to try and understand the etiology and occurrence of these flail movements. Results of this study revealed that individuals suffering flail movements (31% of all the subjects) had longer times of absolute, total, and relative incapacitation.

We consider that +G_z-induced LOC may be more accurately described by dividing the LOC into different subtypes based on the depth of unconsciousness. For convenience, the shorter, noneventful LOC episodes may be termed acute or Type I LOC episodes. The prolonged episodes with associated convulsive movements (flail) and recognizable dreamlike states may be termed more catastrophic, or Type II LOC episodes. The deeper levels of unconsciousness are associated with longer periods of absolute incapacitation and are more frequently associated with flail-like movements and recognizable dreamlike states experienced by the subject.

Seven (13%) of the subjects experienced recognizable dreams during their LOC episodes. The +G_z-induced LOC incapacitation of these individuals is given in Table IV. The mean absolute incapacitation tended to be longer for this symptom subgroup. It is likely that more individuals than reported experienced dreams, but they may not remember the dreams or be reluctant to report the dream. The reluctance to report the dream may result from a psychologic denial (cover-up) tendency as previously reported (4). Episodes of +G_z-induced LOC, therefore, may not only be difficult to recognize by an individual experiencing LOC, but, in addition, there are definite tendencies to deny an episode of losing self-control. Additional symptoms associated with the unconsciousness are listed in Table V.

TABLE V. +G_z-INDUCED LOSS OF CONSCIOUSNESS SYMPTOMS.

1.	Unaware of LOC
2.	Light loss not helpful to prevent LOC
3.	Convulsion (flail) movements, tongue biting
4.	Tingling: extremities, mouth
5.	Dream state
6.	Confusion, altered judgement
7.	Euphoria
8.	Embarrassment
9.	Denial

Exhaustive dissection of +G_z-induced LOC is necessary if a complete understanding of the phenomenon is to be achieved. This complete understanding is necessary to enhance recovery and optimum safety in the aviation environment of the high-performance-aircraft pilot.

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